Salinization of West Michigan Lakes:
Surveying Prevalence, Severity, and Location

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Abstract: The salinization of freshwater ecosystems is a growing concern, especially in north temperate regions due to runoff from de-icing salts. Although several lakes in the Grand Rapids (MI) region have elevated chloride concentrations, the scope of this issue has not been explored empirically in west Michigan; this knowledge gap inspired a 50-lake survey in 5 Michigan Counties to determine the extent of chloride contamination. An additional 4 lakes were included based on prior studies, resulting in a 53-lake data set. Water quality samples were collected from a deep site in each lake, and tested for chloride, conductivity, phosphorus, and other selected parameters. Our results indicated an absence of chloride contamination in our data set with the exception of the previously studied Grand Rapids lakes. Overall, bottom dissolved oxygen and phosphorus concentrations were positively correlated, suggesting internal phosphorus loading is occurring. Land use affected chloride and conductivity with forest land cover being negatively correlated and developed land being positively correlated. In addition, there was a moderately negative correlation between chloride and distance to major roads but a moderately positive correlation between chloride and absolute salt application. The epilimnion and hypolimnion chloride measurements were compared with chloride predictions from an epilimnion model developed by Dugan et al. (2020) and an equilibrium model developed by Solomon et al. (2023). Epilimnion chloride samples generally fell within Dugan et al. (2020) model prediction intervals, while comparison with Solomon et al. (2023) equilibrium concentrations revealed that the sampled lakes have not reached a chloride equilibrium. Because neither model separated epilimnion and hypolimnion chloride concentrations, we developed a Michigan-specific epilimnion and hypolimnion chloride model using our samples and data from the U.S. Water Quality Portal. The MI model predicted greater chloride

concentrations in lakes with urbanized watersheds. In conclusion, while the studied lakes in west Michigan currently are not being impacted by road salt runoff, the correlation data suggest they may be at risk in the future, especially as these inland lakes continue to experience greater use and population density.

Introduction:

Salt density is greater than water; as a consequence, salt entering lakes from tributaries sinks into the hypolimnion. Hence, the surface of a lake may appear healthy but there may be a salt problem that is not visible to lake residents. If the salt density gradient in the lake is strong, the lake will no longer mix (either in part or completely), leaving a relatively salt-free epilimnion but a salinized hypolimnion, where nutrients can accumulate because of continuous inputs but limited biotic uptake. Indeed, we have measured total phosphorus (TP) concentrations exceeding 5000 µg/L in a salt-impacted lake in Grand Rapids (Foley and Steinman 2023). The elevated chloride (Cl^-) levels are potentially toxic to the biota, resulting in changes to the lake food web. In addition, if the lake does ever mix, high nutrient and salt concentrations will reach the photic zone, resulting in algal blooms and/or toxicity to salt-sensitive biota. In effect, the salt issue is a ticking time bomb for the ecological health of the lakes and represents a potential economic risk for lakefront homeowners.

Given the growing use of de-icing salt, the rising Cl^- concentrations in United States waterways (Novotny et al. 2008; Dugan et al. 2020), and the apparent inadequacy of water quality guidelines to protect freshwater biota (Hintz et al., 2022), it is critical to understand both the extent of chloride contamination and what factors are responsible for this growing issue. Indeed, Dugan et al. (2017) estimated that 7,700 lakes in the North American Lakes region are at risk for elevated Cl^- concentrations.

In this study, we examined 53 lakes in the west Michigan region for possible chloride contamination. Our objectives were threefold: 1) measure salt (in the form of chloride), phosphorus, and other water quality parameters in 53 west Michigan lakes to determine their degree of salinization and factors influencing their salt vulnerability; 2) share this information with stakeholders, natural resource managers, and elected officials; and 3) use predictive modeling tools to estimate the prevalence and distribution of lake salinization in Michigan.

Methods:

Site selection. A total of 53 lakes were examined, composed of 50 lakes that were sampled in May-June of 2025, selected primarily based on the presence of a public boat launch (MDNR, 2020). Forty-nine lakes were selected from the 5-county region (Muskegon, Oceana, Mason, Lake, and Newaygo) located within the regional boundaries overseen by the West Michigan Shoreline Regional Development Commission, which is a federal and state designated regional planning and development agency. An additional lake from Ottawa County (Spring Lake) was sampled, resulting in the target of 50 lakes. Three additional lakes from Kent County (Westboro Lake, Middleboro Lake, and Church Lake), sampled between 2021 and 2023, were added to the dataset (Figure 1). The lakes' watersheds and buffer areas have a wide range of road densities, proportions of developed land, and road salt application rates.

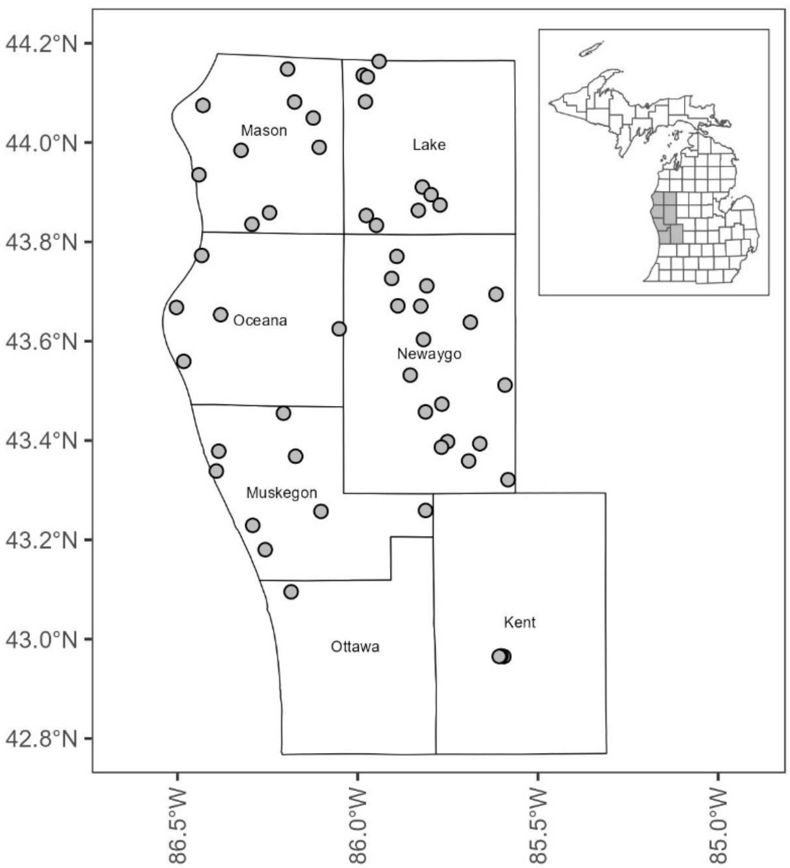


Figure 1. Locations of the 53 lakes sampled by AWRI.

Field methodology. Measurements were made at the deepest site in each lake based on bathymetric maps. Temperature, dissolved oxygen, total dissolved solids, specific conductivity, pH, and turbidity (FNU) measurements were made with a YSI EXO2 multiprobe sonde at 1 m intervals from the surface down to the lake bottom. Secchi disk depth was recorded at each site to measure the water transparency of the lake. Water samples were collected 1 m below the water surface and 1 m above the sediment surface using a Van Dorn water sampler for analysis of Cl^-, total phosphorus (TP), and soluble reactive phosphorus (SRP).

Lab methodology. Water samples were stored on ice during transportation back to the laboratory. Upon return, samples for TP were stored at 4°C and 20 mL samples for SRP and Cl^- were filtered through a 0.45 µm acid-washed filter; SRP was stored at 4°C and Cl^- was frozen at minus 20°C until analysis. TP and SRP were analyzed on a SEAL AQ400 Discrete Analyzer (USEPA, 1993) and Cl^- samples were analyzed by ion chromatography on a Dionex ICS 2100 (APHA, 1999). For TP and SRP, samples less than the detection limit (7 µg/L and 5 µg/L, respectively) were assigned a value of ½ the detection limit (Hornung and Reed, 1990).

Data Analysis and Modeling.

The measurements were compared to two previously developed Cl^- models from Dugan et al. (2020) and Solomon et al. (2023). The Dugan model used machine learning and landscape scale variables (land use, climate, road density) to estimate epilimnion Cl^- concentrations in over 49,000 lakes greater than 4 ha in the Midwest and Northeast United States, including Michigan. Note that epilimnion measurements were defined as <10 m depth from the water surface. The Solomon model used a simple dynamic model considering road salt application and runoff to estimate equilibrium Cl^- concentrations for all lakes in the United States greater than 1 ha, assuming the lakes are well-mixed, exorheic, and constant volume. The Solomon model also assumed constant road salt application rates into the future.

A separate "Michigan Chloride Model" was developed using Random Forest regression (R tidymodels v1.3.0, engine = 'ranger') to predict epilimnion and hypolimnion Cl^- concentrations at all Michigan lakes >1 ha in surface area (n = 15,797). This method is similar to the approach used in Dugan et al. (2020). Separate models were developed for the epilimnion and hypolimnion. Each model was trained on a random sample of 75% of the lakes and independently tested on the remaining 25% (hold-out data). Model parameters were tuned using 10-fold cross validation with five repeats (effectively training and validating the model with 50 unique data partitions). Model performance was evaluated using r^2, root-mean-square error (RMSE), and mean absolute error (MAE). The model parameters that minimized RMSE, resulting in the best fit to the training and testing data, were used to estimate epilimnion and hypolimnion Cl^- concentrations in all Michigan lakes. Scaled variable importance was calculated using permutation importance.

In addition to the samples collected in this study, supplemental Cl^- measurements in Michigan lakes were obtained from the U.S. Water Quality Portal (WQP) to use in model training and testing. Data were filtered to include only measurements collected after January 1, 2000. For epilimnion measurements, these data were filtered again by sample depth (<3 m below water surface), resulting in 215 lakes with Cl^- measurements (including data collected by AWRI, n = 53). For hypolimnion measurements, the WQP data were filtered using the following criterion: sample depth > 5 m below the water surface at which that depth is greater than half of the maximum depth of the lake. Lakes without documented maximum depths were excluded from the data. Lake maximum depth data were obtained from LAGOS-US DEPTH (Webster et al., 2022). When lakes had multiple Cl^- measurements, the median Cl^- concentration was used.

Model predictor variables were obtained primarily at the lake watershed scale from the LAGOS-US Research Platform (Cheruvelil et al. 2021). The selected predictor variables were based on those identified as significant by Dugan et al. (2020), including developed land cover and road density in the lake watershed. In addition, we used the USGS Estimates of Road Salt Application (1992-2019) dataset (Bock et al. 2019) summarized by lake watershed. The USGS road salt data are 1-km spatial resolution and were summarized as annual average application (ton/ha/yr) in each lake watershed. Euclidean distance from each lake to the nearest primary road (interstate highway) or secondary road (main arteries such as U.S./state/county highway) was also included as a variable.

Results and Discussion

Lake survey. There is no indication of road salt contamination in the lakes that we newly sampled as part of this study (Figure 2). The only lakes that exceeded the State of Michigan's chloride threshold of 150 mg/L were from Kent County and were sampled from 2021 through 2023 by the Steinman lab. Those three lakes (Church, Middleboro, and Westboro) also were the only ones with substantially greater Cl^- concentrations in the hypolimnion than in the epilimnion (Figure 2). The close proximity of those hydrologically connected lakes (Molloseau and Steinman 2024) to a major state highway contributed to their high Cl- concentrations. In contrast, the other lakes sampled, while often heavily populated by residences, were not close to major, salted highways (see below).

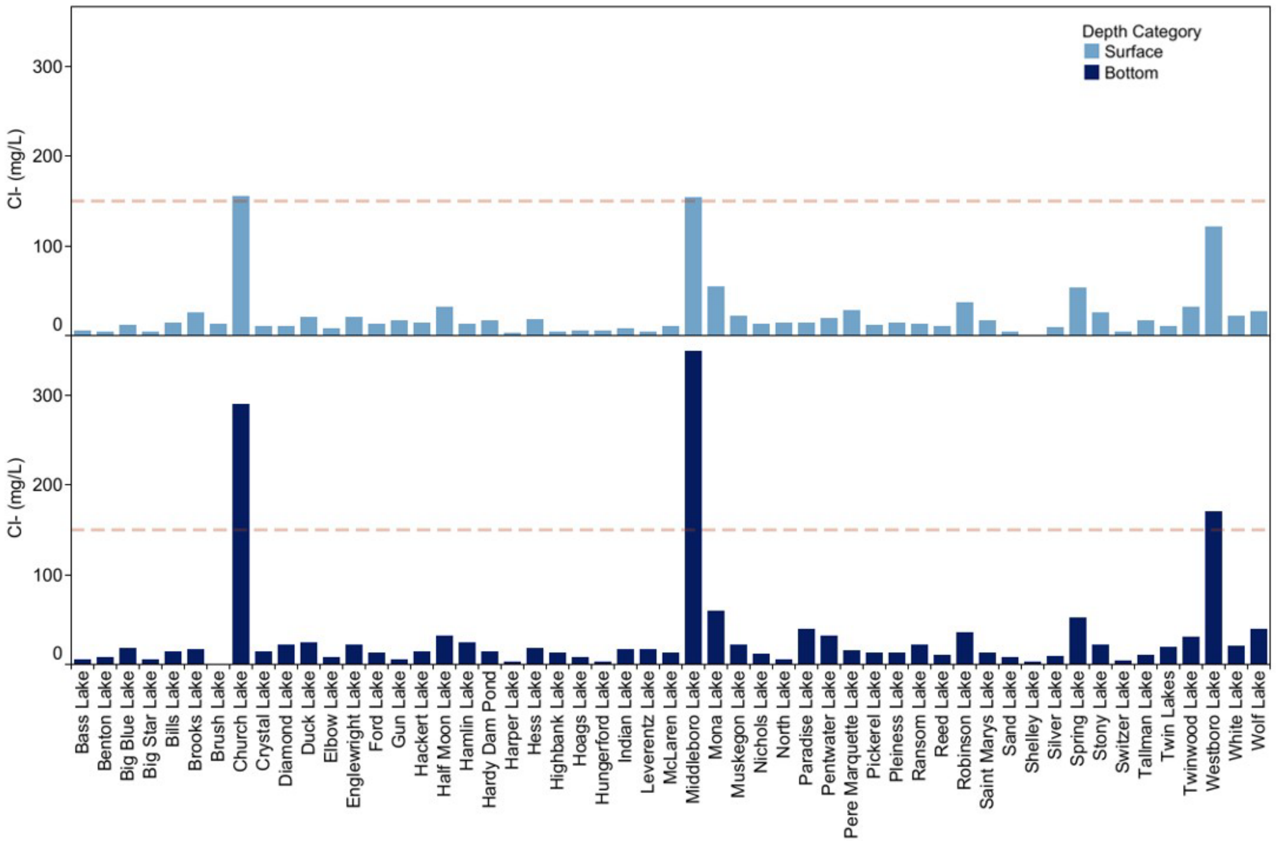


Figure 2. Chloride concentrations 1m below the surface (top panel) and 1m above the bottom (bottom panel) in the 53 lakes. Dashed lines represent the State of Michigan's chloride concentration threshold of 150 mg/L.

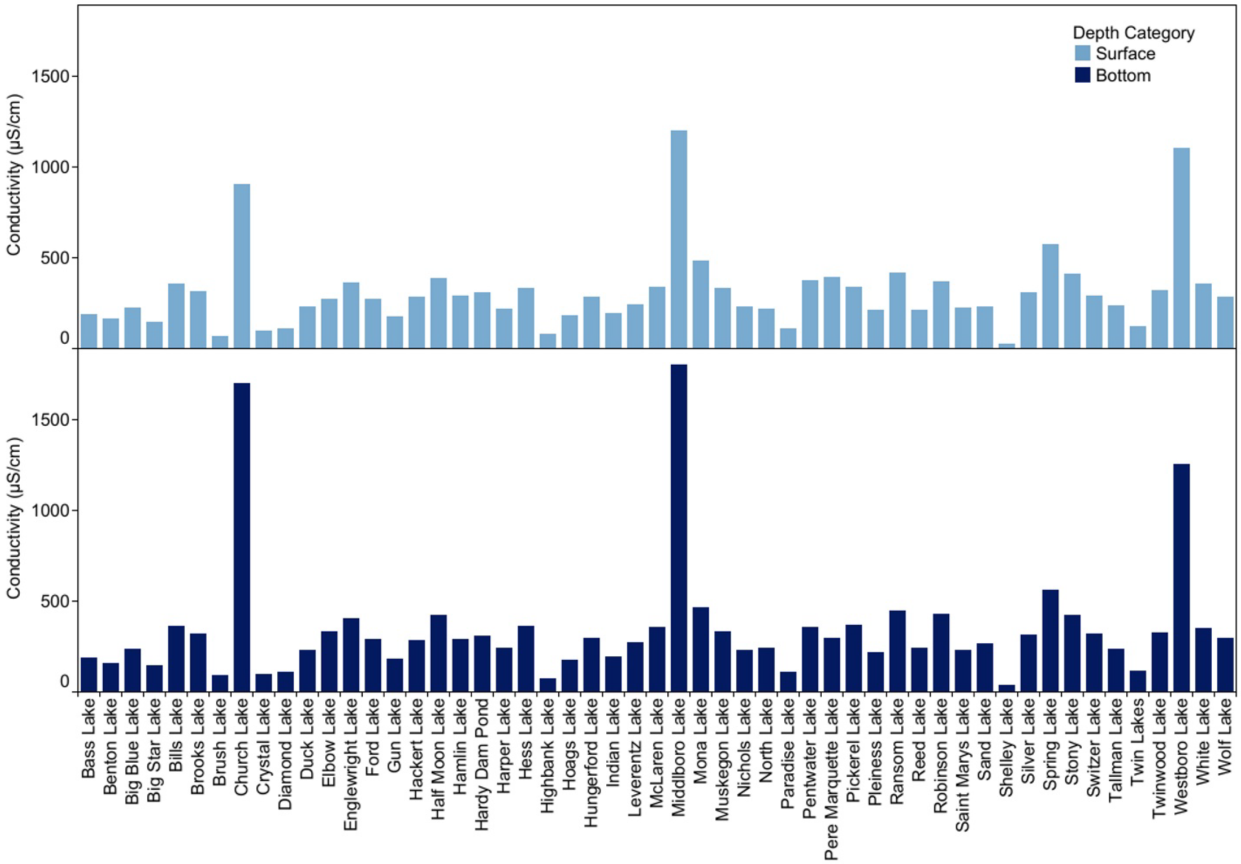


Figure 3. Specific conductivity concentrations 1m below the surface (top panel) and 1m above the bottom (bottom panel) in the 53 lakes.

Our prior studies revealed a strong relationship between specific conductivity and Cl^- in Church Lake ($r^2 = 0.92$; Foley and Steinman 2023). Hence, we were not surprised to find that conductivity followed a very similar pattern as Cl^- in the sampled lakes (Figure 3).

TP concentrations in the near surface waters were relatively low (< 40 µg/L) in all the lakes included in our study (Figure 4). Even Church, Middleboro, and Westboro Lakes, with high salt concentrations in the hypolimnion forming a halocline due to salt sinking to the bottom, maintained modest TP concentrations in the epilimnion because the phytoplankton and aquatic vegetation in the littoral zones assimilate bioavailable P. In the other lakes, which are typically dimictic, spring and fall turnover help to mix the bottom nutrients and biotic uptake maintains a TP balance.

In the hypolimnion, the situation is different for the three salt-impacted lakes (Figure 4), where TP concentrations were exceedingly high (> 1700 µg/L), as the limited mixing allowed phosphorus to accumulate. TP concentrations in Half Moon and Pickeral Lakes were in excess of 220 µg/L and all the other lakes were < 100 µg/L (Figure 4).

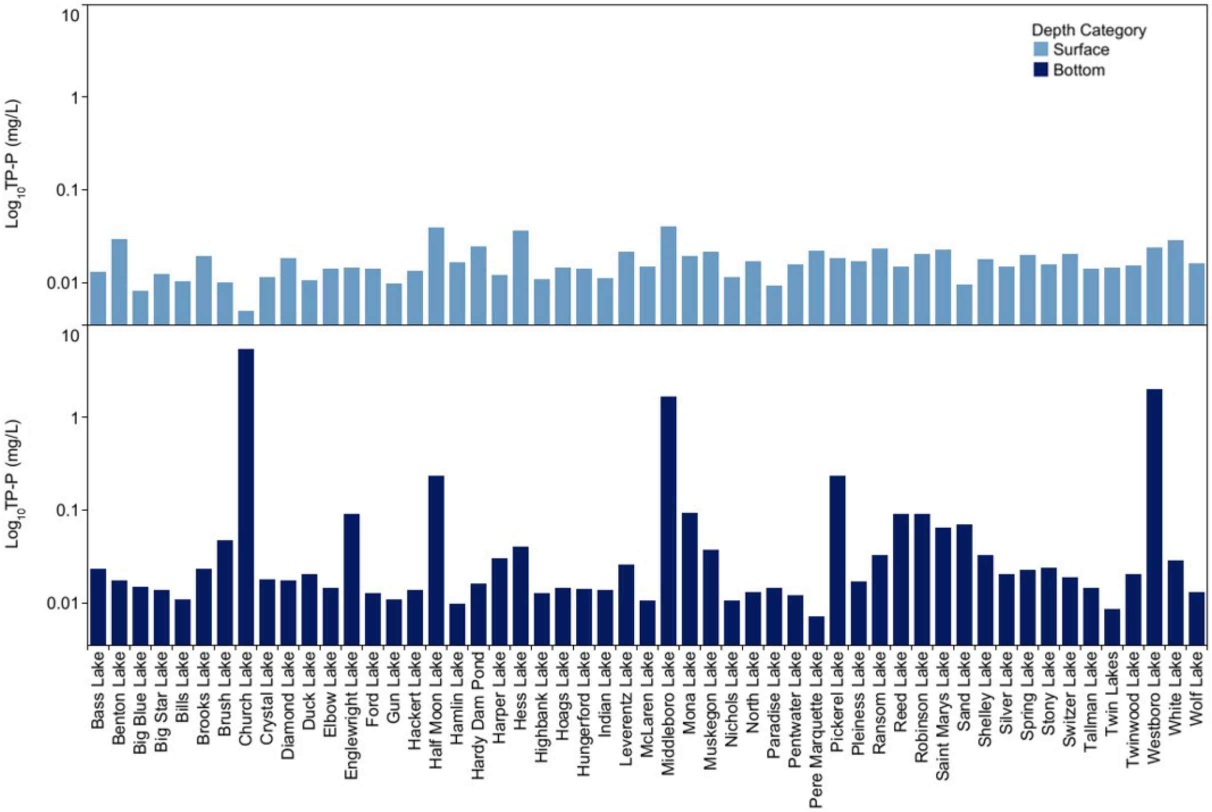


Figure 4. Log$_{10}$ total phosphorus concentrations 1m below the surface (top panel) and 1m above the bottom (bottom panel) in the 53 lakes.

Soluble reactive phosphorus concentrations were similar to TP with elevated hypolimnetic concentrations at the three salt-impacted lakes. Four other lakes had bottom SRP concentrations in excess of 60 µg/L but all the remaining lakes were < 20 µg/L (Figure 5).

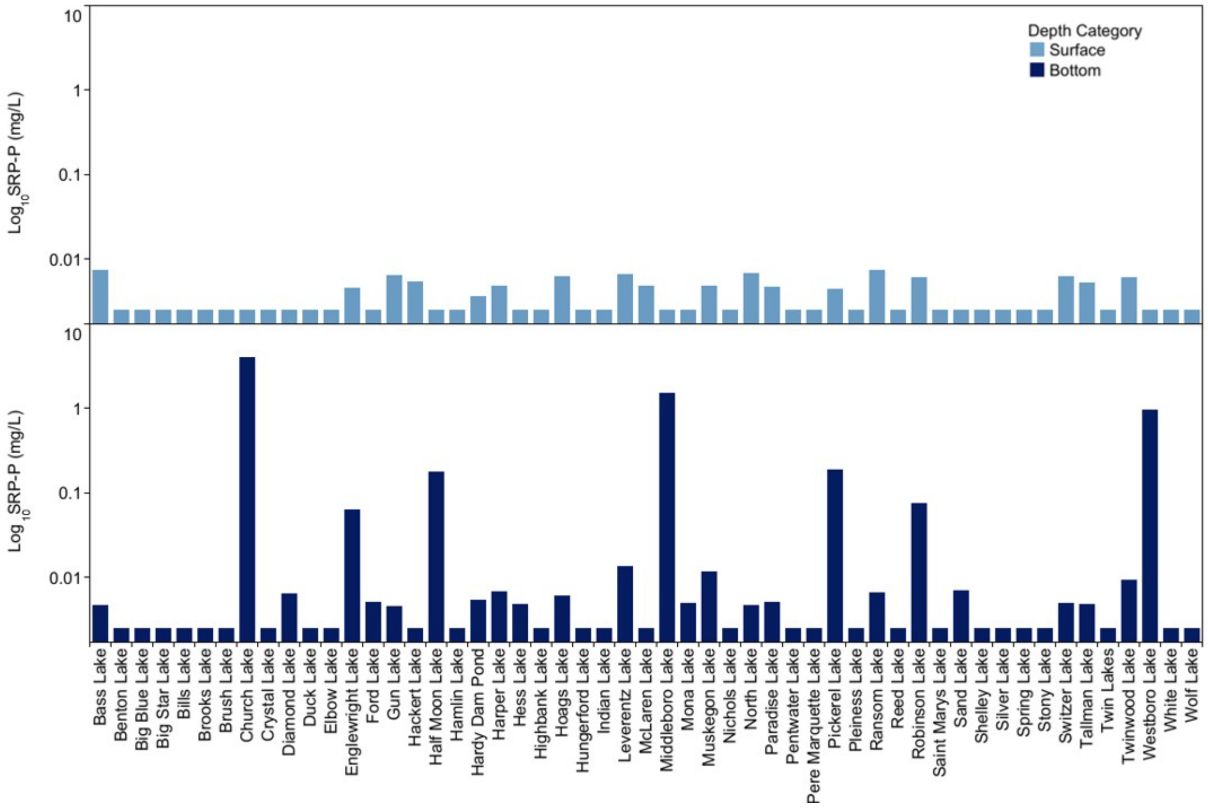


Figure 5. Log$_{10}$ soluble reactive phosphorus concentrations 1m below the surface (top panel) and 1m above the bottom (bottom panel) in the 53 lakes.

Dissolved oxygen (DO) concentrations in the surface waters of all 53 lakes were generally high (> 6 mg/L), indicative of healthy conditions (Figure 6). However, near-bottom DO levels were hypoxic to anoxic in several lakes; as expected, this applied to the three salt-impaired lakes, where the hypolimnion is often isolated from oxygenated waters. The two other lakes with elevated bottom TP concentrations (Pickerel and Half Moon Lakes) also had very low DO concentrations. These lakes, as well as Robinson and Englewright Lakes, all had elevated SRP and low DO concentrations (Figures 4, 6). This suggests that a number of lakes in our survey, despite having low chloride levels, are experiencing internal phosphorus loading from the sediments (Steinman and Spears 2020). In contrast, Foley and Steinman (2023) measured low rates of sediment phosphorus release from Church Lake, the lake with the greatest degree of salt impairment in our survey.

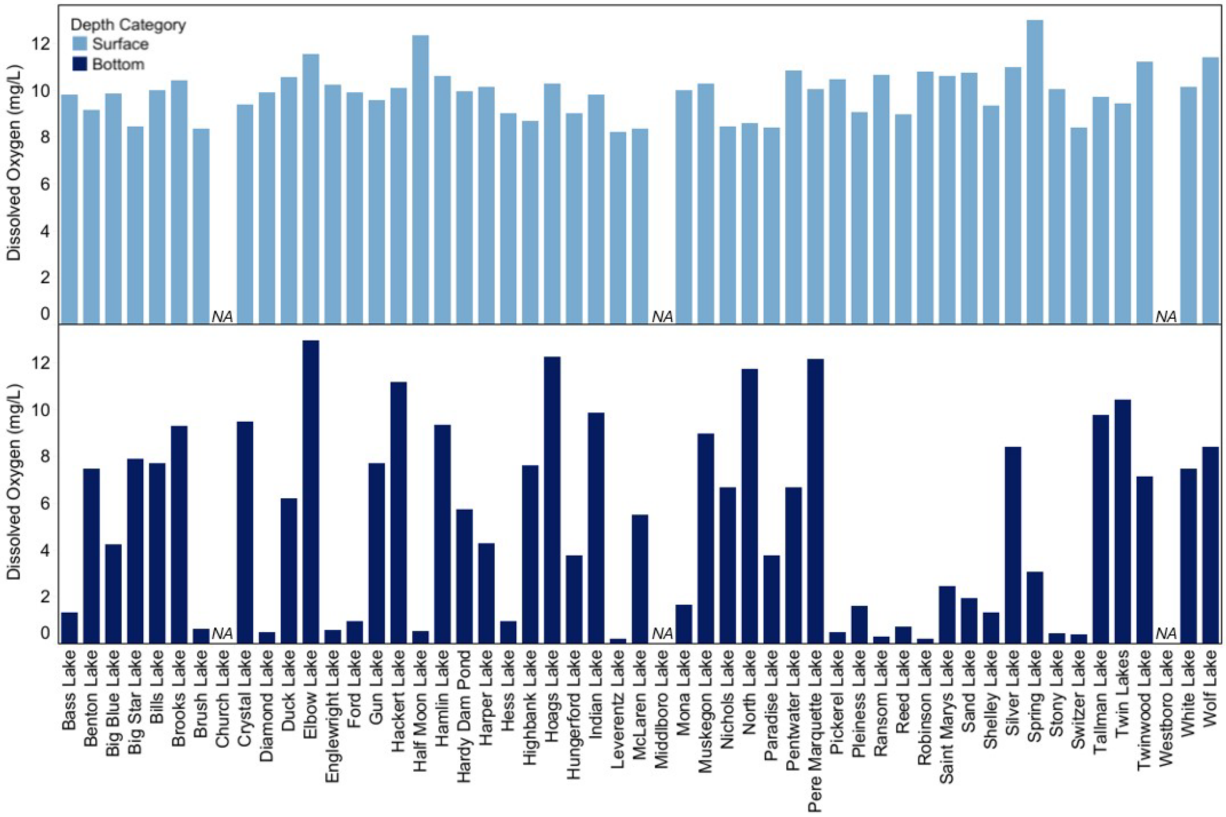
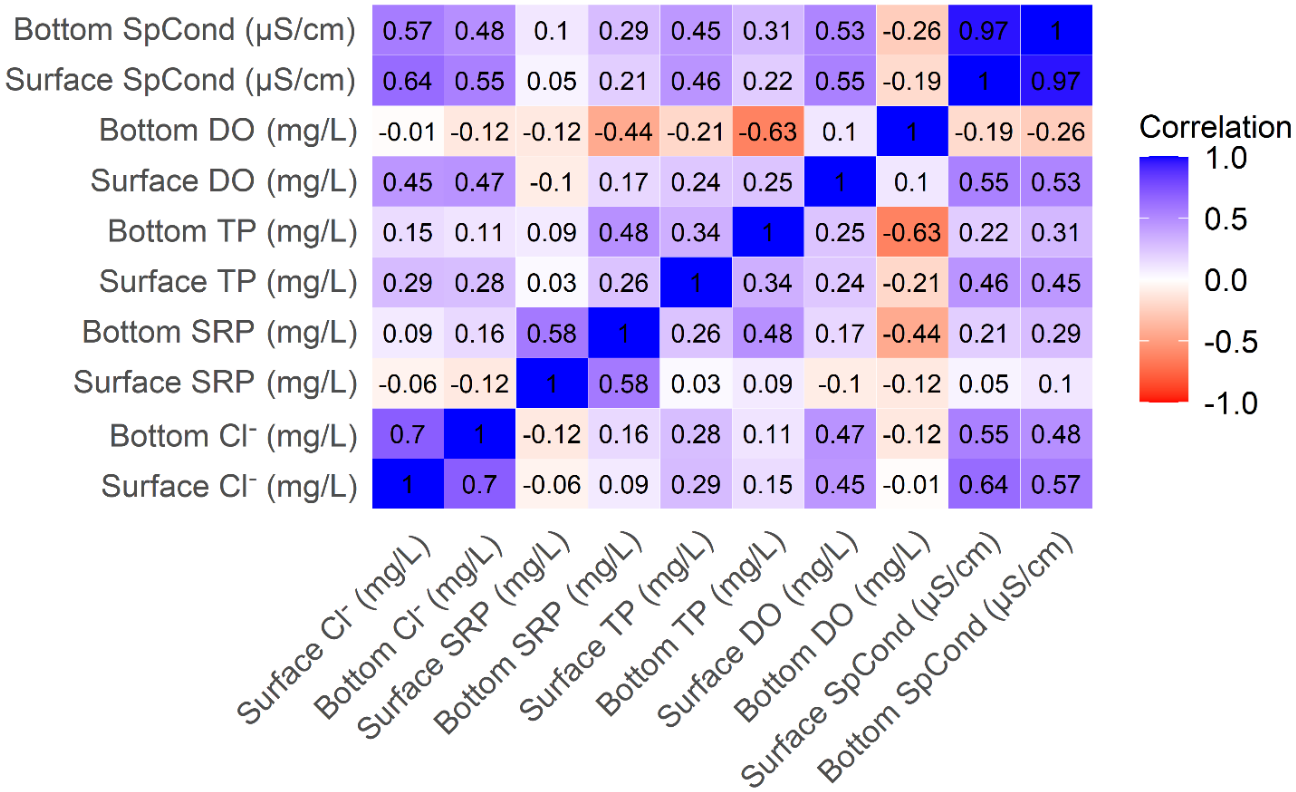


Figure 6. Dissolved oxygen concentrations 1m below the surface (top panel) and 1m above the bottom (bottom panel) in the 53 lakes.

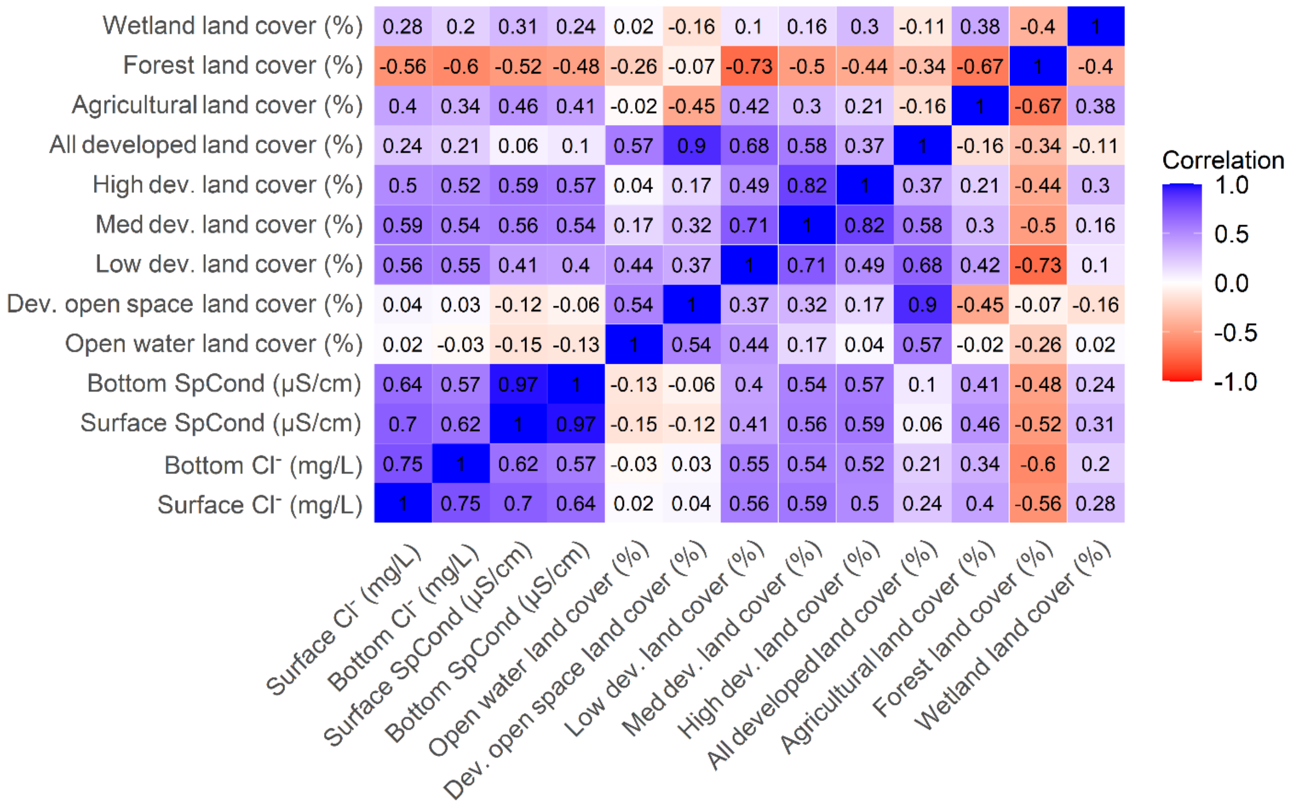
We generated three Spearman correlation matrices to examine which variables may be related to lake chloride and conductivity levels. The three focused on environmental factors, land use factors, and road-related factors. For the environment matrix (Figure 7), the bottom and surface Cl^- concentrations were highly correlated, suggesting overall there was no indication of a halocline forming in these lakes. In addition, there was a moderately strong correlation between Cl^- and conductivity (0.70), suggesting conductivity could be used as a proxy for chloride concentration. There was a moderately strong negative correlation (-0.63) between bottom DO and Bottom TP, further supporting the notion that internal phosphorus loading may be present in many of these lakes (Figure 7).



	Surface Cl$^-$ (mg/L)	Bottom Cl$^-$ (mg/L)	Surface SRP (mg/L)	Bottom SRP (mg/L)	Surface TP (mg/L)	Bottom TP (mg/L)	Surface DO (mg/L)	Bottom DO (mg/L)	Surface SpCond (µS/cm)	Bottom SpCond (µS/cm)
Bottom SpCond (µS/cm)	0.57	0.48	0.1	0.29	0.45	0.31	0.53	-0.26	0.97	1
Surface SpCond (µS/cm)	0.64	0.55	0.05	0.21	0.46	0.22	0.55	-0.19	1	0.97
Bottom DO (mg/L)	-0.01	-0.12	-0.12	-0.44	-0.21	-0.63	0.1	1	-0.19	-0.26
Surface DO (mg/L)	0.45	0.47	-0.1	0.17	0.24	0.25	1	0.1	0.55	0.53
Bottom TP (mg/L)	0.15	0.11	0.09	0.48	0.34	1	0.25	-0.63	0.22	0.31
Surface TP (mg/L)	0.29	0.28	0.03	0.26	1	0.34	0.24	-0.21	0.46	0.45
Bottom SRP (mg/L)	0.09	0.16	0.58	1	0.26	0.48	0.17	-0.44	0.21	0.29
Surface SRP (mg/L)	-0.06	-0.12	1	0.58	0.03	0.09	-0.1	-0.12	0.05	0.1
Bottom Cl$^-$ (mg/L)	0.7	1	-0.12	0.16	0.28	0.11	0.47	-0.12	0.55	0.48
Surface Cl$^-$ (mg/L)	1	0.7	-0.06	0.09	0.29	0.15	0.45	-0.01	0.64	0.57

Figure 7. Spearman correlation coefficient matrix of environmental variables from the 53 lakes.

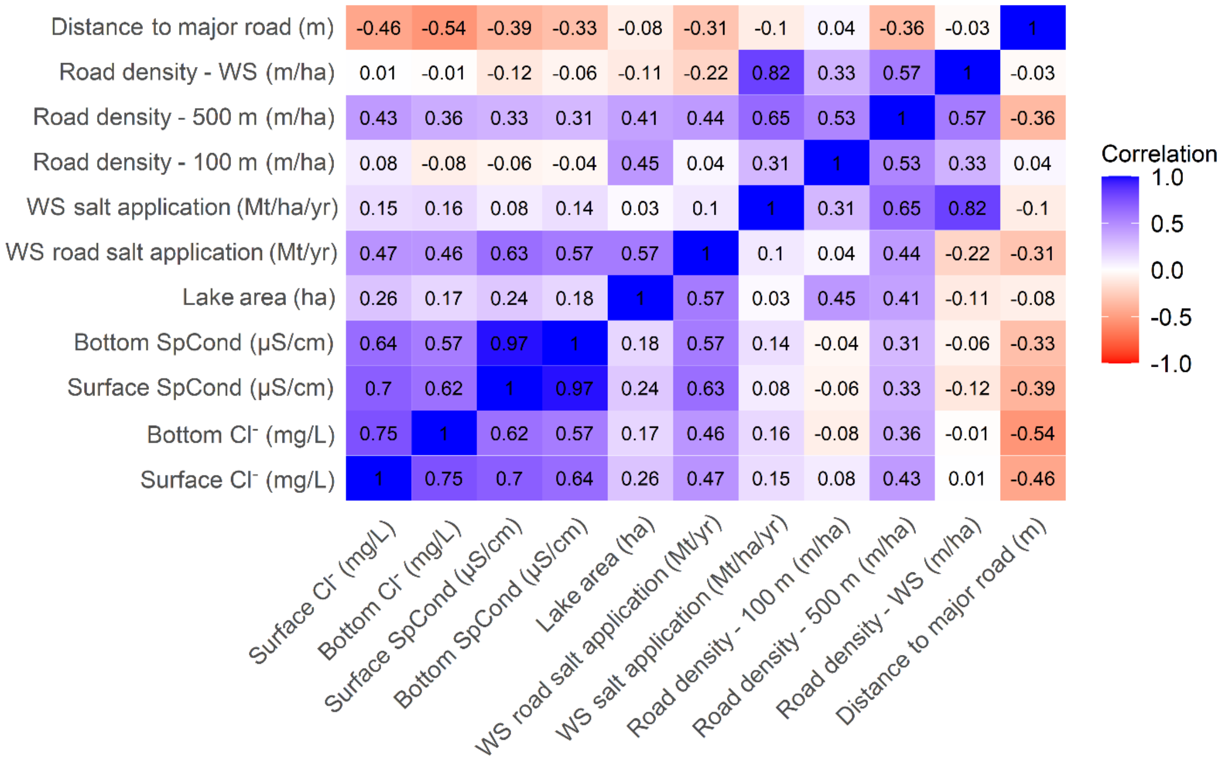
For the land use variables matrix (Figure 8), there was a moderately negative relation between forest cover and surface and bottom Cl/conductivity (-0.48 to -0.60), which is consistent with the ability of forest soils to retain salts (Johnson et al. 1986; David et al. 1991), as well as low road density and therefore, low salt application. There also was a moderately positive relation between developed land and Cl$^-$/conductivity (0.50 to 0.59), which may be related to the proximity of roads to lakes receiving runoff from the deicing salt (Dugan et al. 2017).



	Surface Cl⁻ (mg/L)	Bottom Cl⁻ (mg/L)	Surface SpCond (μS/cm)	Bottom SpCond (μS/cm)	Open water land cover (%)	Dev. open space land cover (%)	Low dev. land cover (%)	Med dev. land cover (%)	High dev. land cover (%)	All developed land cover (%)	Agricultural land cover (%)	Forest land cover (%)	Wetland land cover (%)
Wetland land cover (%)	0.28	0.2	0.31	0.24	0.02	-0.16	0.1	0.16	0.3	-0.11	0.38	-0.4	1
Forest land cover (%)	-0.56	-0.6	-0.52	-0.48	-0.26	-0.07	-0.73	-0.5	-0.44	-0.34	-0.67	1	-0.4
Agricultural land cover (%)	0.4	0.34	0.46	0.41	-0.02	-0.45	0.42	0.3	0.21	-0.16	1	-0.67	0.38
All developed land cover (%)	0.24	0.21	0.06	0.1	0.57	0.9	0.68	0.58	0.37	1	-0.16	-0.34	-0.11
High dev. land cover (%)	0.5	0.52	0.59	0.57	0.04	0.17	0.49	0.82	1	0.37	0.21	-0.44	0.3
Med dev. land cover (%)	0.59	0.54	0.56	0.54	0.17	0.32	0.71	1	0.82	0.58	0.3	-0.5	0.16
Low dev. land cover (%)	0.56	0.55	0.41	0.4	0.44	0.37	1	0.71	0.49	0.68	0.42	-0.73	0.1
Dev. open space land cover (%)	0.04	0.03	-0.12	-0.06	0.54	1	0.37	0.32	0.17	0.9	-0.45	-0.07	-0.16
Open water land cover (%)	0.02	-0.03	-0.15	-0.13	1	0.54	0.44	0.17	0.04	0.57	-0.02	-0.26	0.02
Bottom SpCond (μS/cm)	0.64	0.57	0.97	1	-0.13	-0.06	0.4	0.54	0.57	0.1	0.41	-0.48	0.24
Surface SpCond (μS/cm)	0.7	0.62	1	0.97	-0.15	-0.12	0.41	0.56	0.59	0.06	0.46	-0.52	0.31
Bottom Cl⁻ (mg/L)	0.75	1	0.62	0.57	-0.03	0.03	0.55	0.54	0.52	0.21	0.34	-0.6	0.2
Surface Cl⁻ (mg/L)	1	0.75	0.7	0.64	0.02	0.04	0.56	0.59	0.5	0.24	0.4	-0.56	0.28

Figure 8. Spearman correlation coefficient matrix of land use variables with chloride and conductivity from the 53 lakes.

For the matrix of road-related variables, there was a moderately negative relationship between Cl^-/conductivity and distance to major road (-0.33 to -0.54; Figure 9); as noted above, this is likely due to ease of deicing salt runoff to reach the lakes through either surface water or groundwater (Novotny et al. 2008; Dugan et al. 2017; Mackie et al. 2022). Absolute salt application (mT/yr) was moderately related to Cl^-/conductivity (0.46 to 0.63). However, when salt application was weighted by area (mT/ha/yr), this relationship weakened considerably, though coefficients remained positive (0.08 to 0.16). When examining the influence of road density at three scales (100m from lake; 500m from lake, whole watershed), the strength of the relationship to chloride and conductivity peaked at the intermediate (500m) distance (Figure 9); while one may expect the relationship would be strongest at road density closest to the lake, it may be given the rural nature of these lakes that roads closest the lakes do not receive much salt application.



	Surface Cl^- (mg/L)	Bottom Cl^- (mg/L)	Surface SpCond (µS/cm)	Bottom SpCond (µS/cm)	Lake area (ha)	WS road salt application (Mt/yr)	WS salt application (Mt/ha/yr)	Road density - 100 m (m/ha)	Road density - 500 m (m/ha)	Road density - WS (m/ha)	Distance to major road (m)
Distance to major road (m)	-0.46	-0.54	-0.39	-0.33	-0.08	-0.31	-0.1	0.04	-0.36	-0.03	1
Road density - WS (m/ha)	0.01	-0.01	-0.12	-0.06	-0.11	-0.22	0.82	0.33	0.57	1	-0.03
Road density - 500 m (m/ha)	0.43	0.36	0.33	0.31	0.41	0.44	0.65	0.53	1	0.57	-0.36
Road density - 100 m (m/ha)	0.08	-0.08	-0.06	-0.04	0.45	0.04	0.31	1	0.53	0.33	0.04
WS salt application (Mt/ha/yr)	0.15	0.16	0.08	0.14	0.03	0.1	1	0.31	0.65	0.82	-0.1
WS road salt application (Mt/yr)	0.47	0.46	0.63	0.57	0.57	1	0.1	0.04	0.44	-0.22	-0.31
Lake area (ha)	0.26	0.17	0.24	0.18	1	0.57	0.03	0.45	0.41	-0.11	-0.08
Bottom SpCond (µS/cm)	0.64	0.57	0.97	1	0.18	0.57	0.14	-0.04	0.31	-0.06	-0.33
Surface SpCond (µS/cm)	0.7	0.62	1	0.97	0.24	0.63	0.08	-0.06	0.33	-0.12	-0.39
Bottom Cl^- (mg/L)	0.75	1	0.62	0.57	0.17	0.46	0.16	-0.08	0.36	-0.01	-0.54
Surface Cl^- (mg/L)	1	0.75	0.7	0.64	0.26	0.47	0.15	0.08	0.43	0.01	-0.46

Figure 9. Spearman correlation coefficient matrix of road related variables with chloride and conductivity from the 53 lakes.

<u>*Comparison to previous chloride models*</u>. We compared the survey results to two previously developed chloride models from Dugan et al. (2020) and Solomon et al. (2023). The Dugan et al. (2020) model generally underestimated chloride concentrations in the lakes that were surveyed as part of the present study, as most fall below the 1:1 line (Figure 10) for both surface and bottom measurements. However, the 5th and 95th percentile prediction intervals envelop 49 of the 51 surface chloride measurements and 44 of the 51 bottom chloride measurements (Figure 11). Only 51 of the 53 lakes were compared because Westboro Lake and Switzer Lake were

excluded due to their size being smaller than 4 ha in surface area, and hence not included in the Dugan et al. model.

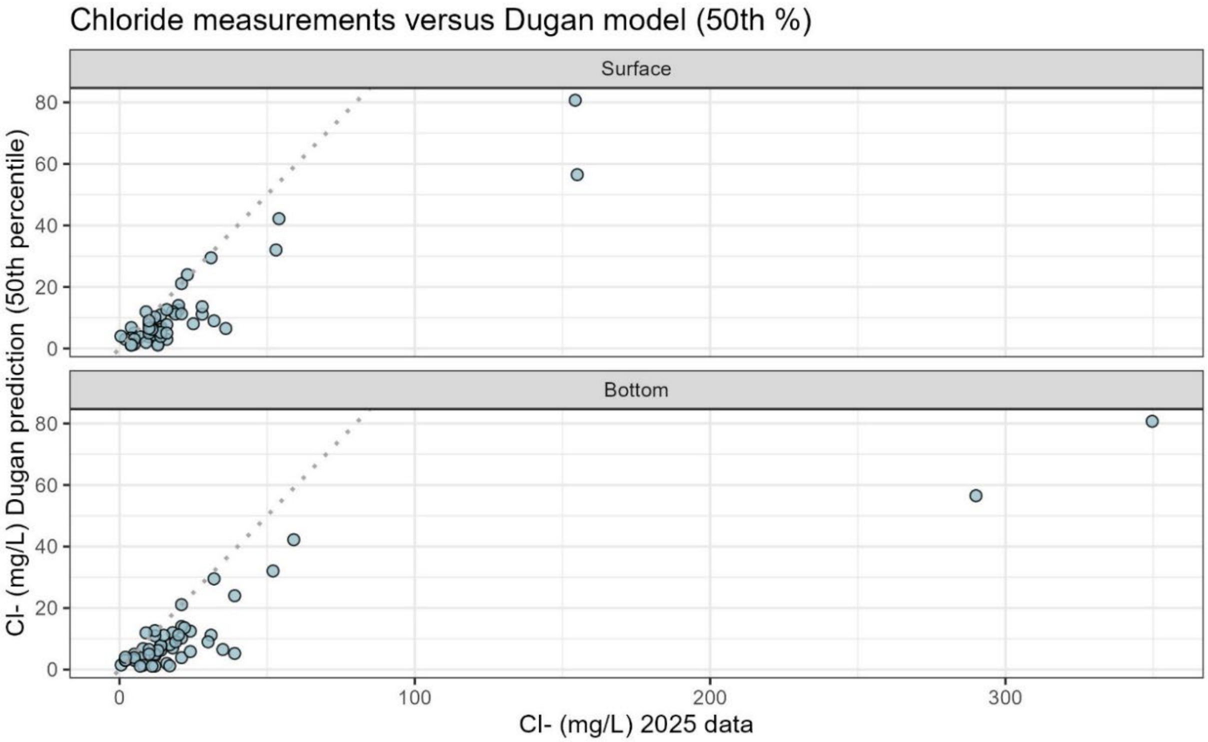


Figure 10. Dugan et al. (2020) median predictions compared to surface (top panel) and bottom (bottom panel) measurements.

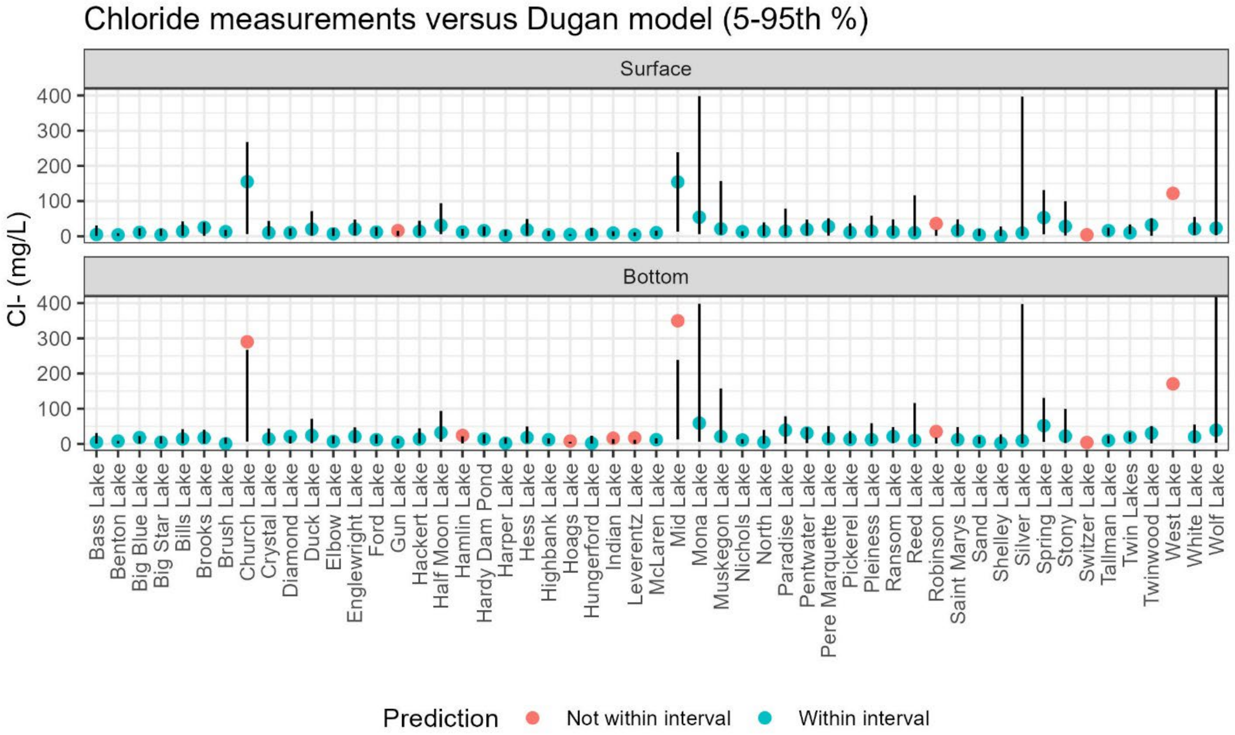


Figure 11. Dugan et al. (2020) 5th-95th percentile prediction intervals compared to surface (top panel) and bottom (bottom panel) measurements. Black vertical lines represent middle 90% prediction interval.

Solomon et al. (2023) predicted equilibrium chloride concentrations given current road salt application rates for all lakes greater than 1 ha in the United States. A comparison between our sampled lakes and equilibrium predictions from Solomon et al. (2023) demonstrate that most lakes have not reached equilibrium chloride concentrations, as indicated by being above the 1:1 line in Figure 12. However, Solomon et al. (2023) note that the simplistic hydrologic nature of their model means the model is best suited for understanding broad scale variation in equilibrium road salt chloride concentrations in response to landscape/climate characteristics and road salt application rates. Hence, comparisons of individual lakes to their overall model should be made cautiously.

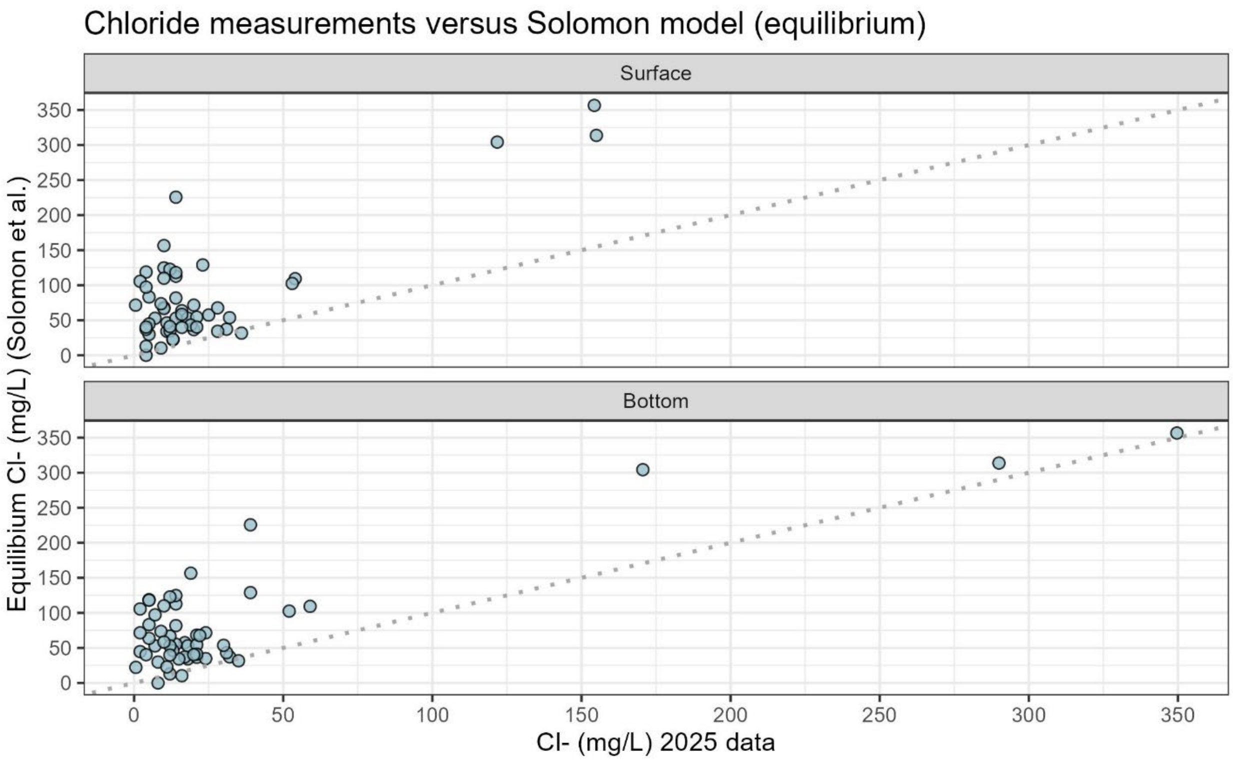


Figure 12. Solomon et al. (2023) equilibrium chloride concentrations compared to the surface (top panel) and bottom (bottom panel) chloride concentrations. A lake is at equilibrium chloride concentration if it falls on the 1:1 line.

<u>Michigan chloride model</u>. The Michigan model (epilimnion and hypolimnion) performance on independent hold-out data (in this case, 25% of the lakes with measurements were held out for model training while the remainder were used for model validation and testing) is presented in Table 1. The model generally performs well based on the performance metrics, although it overestimates at lakes with lower chloride concentrations (Figure 13). However, error is greatest in lakes with high (>50 mg/L) Cl^- concentrations. The varying model performance as a function of chloride concentration is likely due to the heavily right-skewed nature of the measurement data, with most lakes having relatively low Cl^- concentrations (the models ‘see’ more of these data). As a rule in models such as these, additional samples would improve predictions, especially in lakes where we are currently estimating high Cl^- concentrations.

Notably, the models were built on relatively scarce data compared to the total number of lakes in Michigan; only 1.36% of lakes (n=215) have epilimnion Cl^- measurements and 0.76% (120) of lakes have hypolimnion chloride measurements since 2000.

Table 1. Model performance metrics on hold-out test datasets

Model	*n (test)*	*RMSE*	*MAE*	*r^2*
Epilimnion	*56*	*14.08*	*8.2*	*0.76*
Hypolimnion	*32*	*28.98*	*14.0*	*0.84*

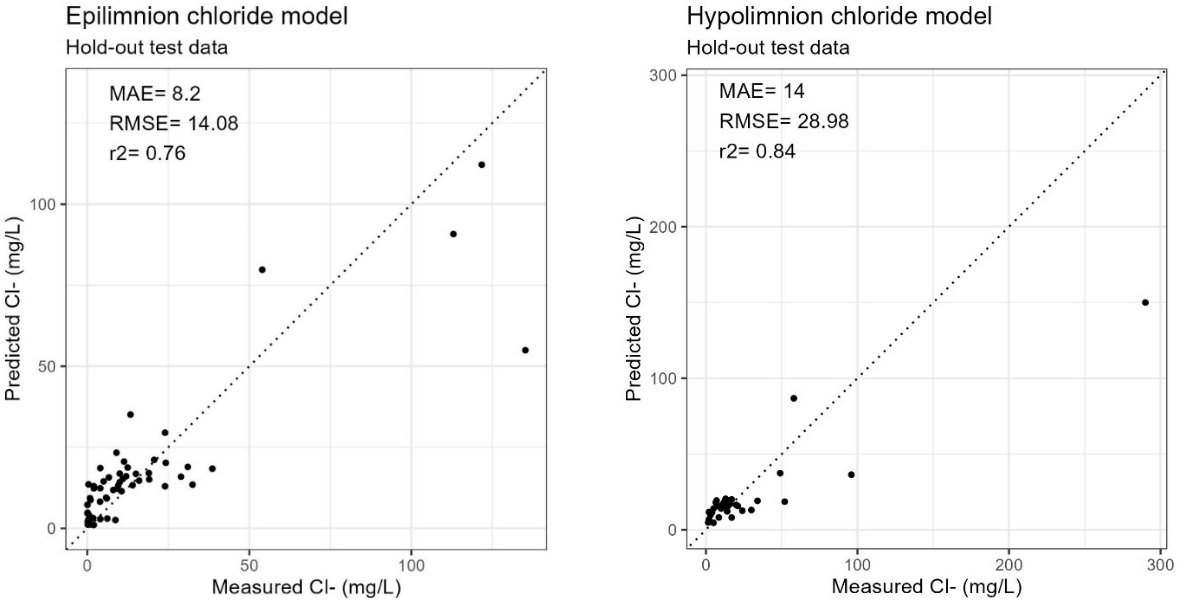


Figure 13. Measured versus predicted chloride concentrations on hold-out test datasets for epilimnion model (left) and hypolimnion model (right). Note differing x and y axis scales for each graph.

The models' variable importance plots (Figure 14) reveal that the most influential predictor variables were various levels of development intensity (medium, low, and high) and road salt application rates (mt/ha/yr). The importance of the normalized salt application rate contrasts with the results from the correlation matrix (Figure 9), where the absolute application rate (mt/yr) has a much greater correlation coefficient (~0.47) than the normalized application rate (mt/ha/yr; ~0.16). We explored this in more detail (Figure 15), and it became apparent that the reason for the inflated influence of the normalized salt application rate was because of the 3 Kent County lakes with increased Cl^- levels at high normalized application rates. This stems from their relatively small watersheds but very high chloride levels.

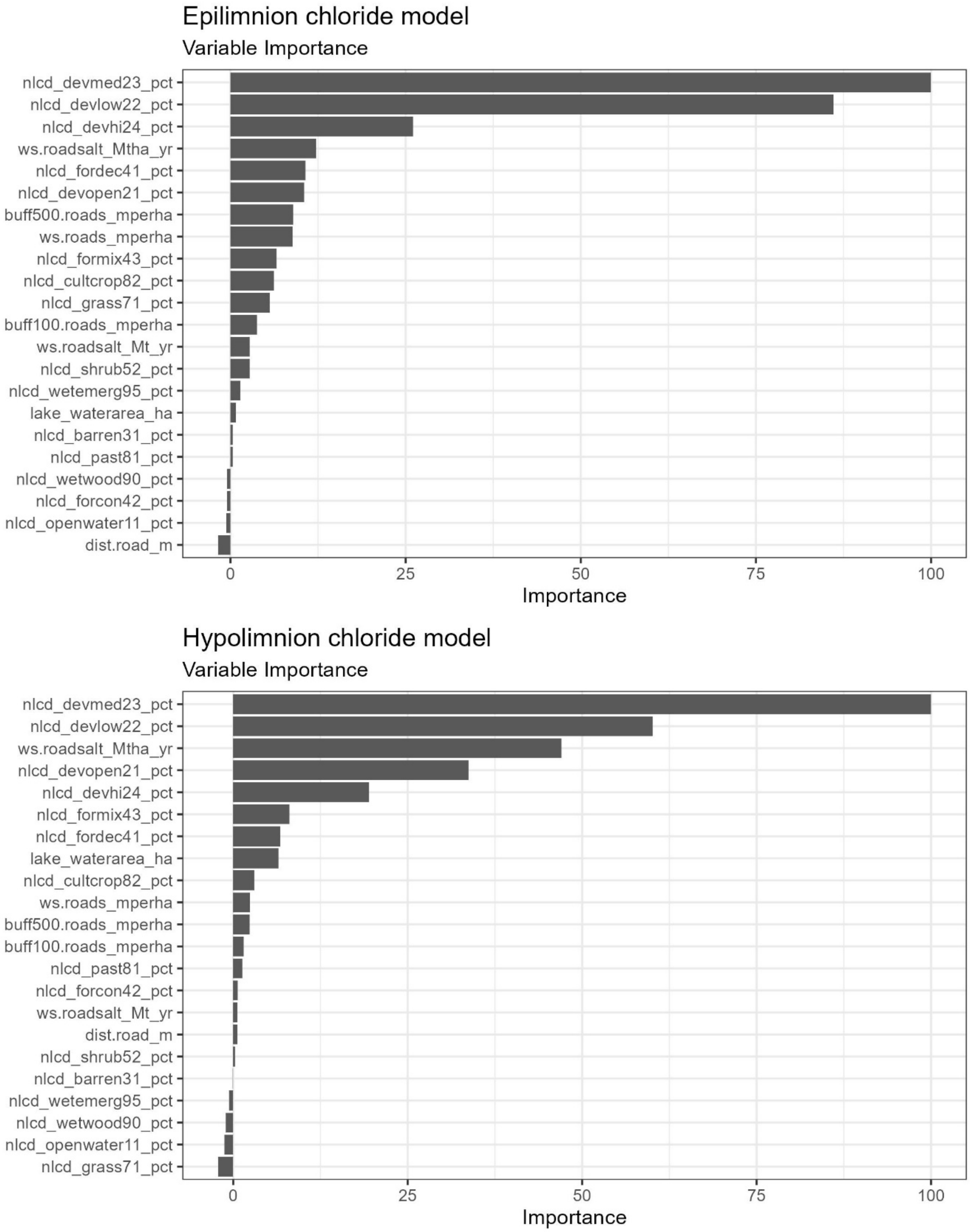


Figure 14. Variable importance plots using scaled permutation importance for the epilimnion model (top) and hypolimnion model (bottom).

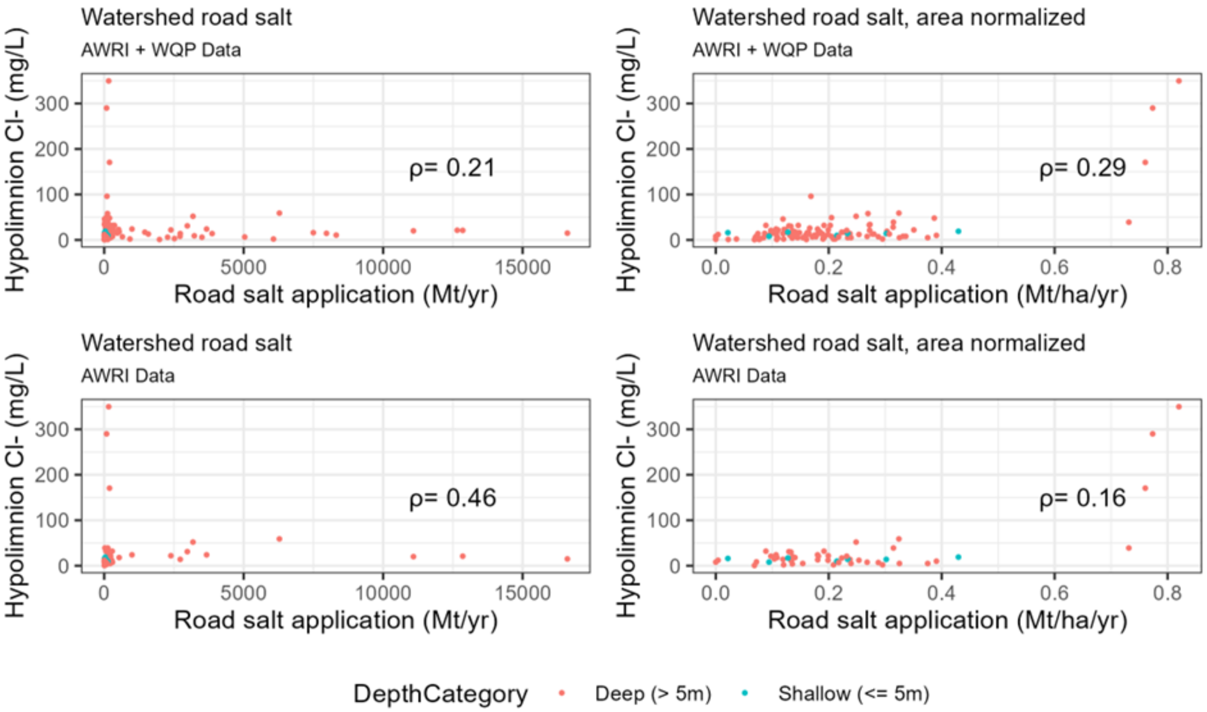
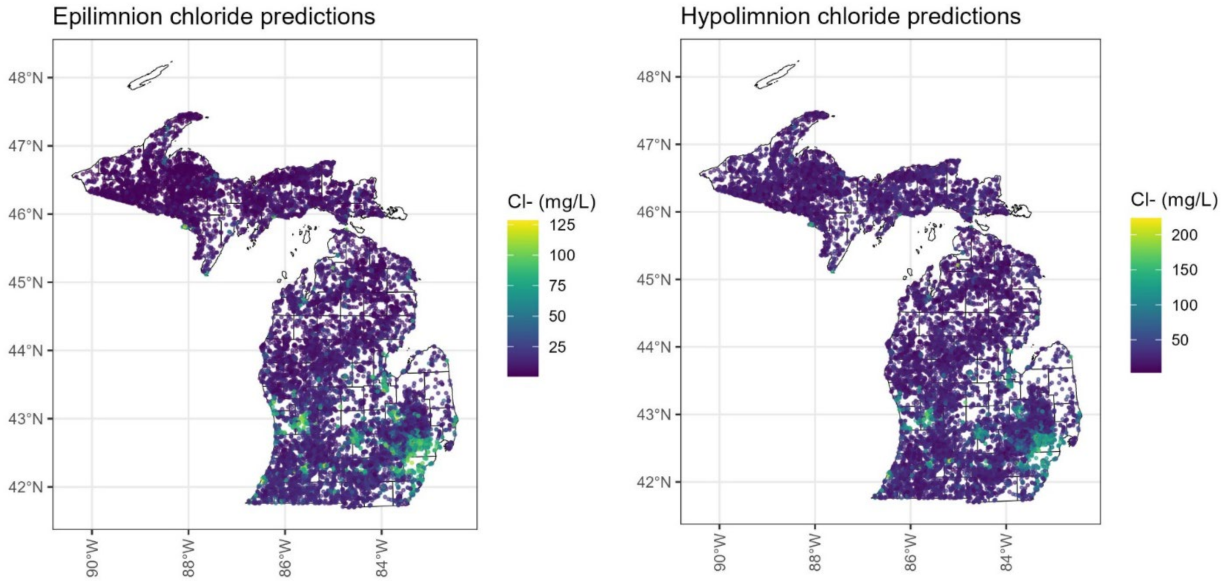


Figure 15. Hypolimnetic chloride concentrations vs. road salt application rates. Plots on the left are absolute rates; plots on the right are normalized rates. Plots on the top include all data; plots on the bottom are data only from current study.

The development variables were also identified as the most important in Dugan et al. (2020) and road salt application rates were not included. Notably, unlike Dugan et al. (2020), distance to primary and secondary roads (interstates and US/state/county highways) did not add value to the models.

The epilimnion and hypolimnion models were applied to 15,797 lakes in Michigan (Figure 16). The median predicted epilimnion chloride concentration for all lakes was 10.8 mg/L (min = 0.5 mg/L, max = 128.6 mg/L), and the median predicted hypolimnion chloride concentration was 24.8 mg/L (min = 3.1 mg/L, max = 223.9 mg/L). The spatial trends of epilimnion and hypolimnion predictions are similar, with hotspots of relatively high chloride concentrations located in urban areas in the Lower Peninsula, such as southeast Michigan, Lansing, and Grand Rapids. As we noted previously, chloride measurements in Michigan lakes are scarce compared to the total number of lakes. The maps created here identify potential hotspots of chloride contamination and can serve as a guide to expand the survey of lake salinization in Michigan in a systematic, stratified approach.


Epilimnion chloride predictions

Hypolimnion chloride predictions

Figure 16. Chloride predictions for 15,797 Michigan lakes for the epilimnion model (left) and hypolimnion (right). Note differing magnitudes in color scales used to optimize differences and highlight hotspots among lakes within each plot.

Conclusions.

Results from the current study indicate that most of the west Michigan lakes surveyed do not have salt impairments and in fact, have chloride concentrations far below the 150 mg/L chronic threshold in Michigan. While this runs counter to modeling outputs suggesting many Midwest lakes are impacted by salt runoff (e.g., Dugan et al. 2020), most of the lakes included in this study were located in rural, low-populated areas where road salt applications are low. The Michigan lakes where salt contamination has been documented are from more populated areas, such as Ann Arbor (Hawkins and Judd 1972), Kalamazoo (Koretsky et al. 2012), and Grand Rapids (Foley and Steinman 2023).

Management implications stemming from these results depend heavily on salt application rates, which are reported at very coarse levels, if at all. Hence, our results need to be viewed with some caution. Until salt application rates are recorded at a finer scale, assumptions such as salt application is uniform throughout a county will limit the ability to predict impacts. Nonetheless, the water quality data from this study clearly indicate that road salt impacts currently are not a significant issue in the overwhelming majority of lakes that we sampled.

The correlation analyses conducted on west Michigan lakes reveal that even with the low chloride concentrations, factors such as developed land use and road density are positively related to chloride and conductivity levels. This suggests that if development around these lakes continues to occur, they too may be threatened by road salt runoff. Hence, it is recommended that planning officials and road commissions consider the following recommendations: 1) monitor heavily populated lakes in their municipality for chloride (or conductivity at a minimum) concentrations every 3 to 5 years at surface and bottom depths of the lake's deepest point; 2) record salt application rates on a highway mileage basis that is GPS-logged; and 3) apply salt in the most environmentally friendly manner while still prioritizing road safety. Wisconsin Salt Wise (https://www.wisaltwise.com/) has a number of best management practices regarding road salt application that can be applied in Michigan to help prevent or reduce salt contamination in our Michigan waterways.

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Supplemental Information:

Final abstract: please see report above

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Other: Ashtyn: NASA DEVELOP program intern

Media story: https://www.fox17online.com/news/local-news/lakeshore/muskegon/salt-study-researchers-set-to-sample-water-from-50-west-michigan-lakes#google_vignette